AD-A093 643   NAVAL RESEARCH LAB WASHINGTON DC   F/G 22/2
ENVIRONMENTAL CONSTRAINTS IN EARTH-SPACE PROPAGATON.(U)
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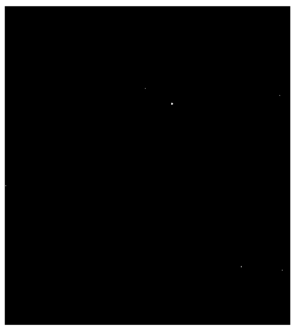

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. ~~REPORT NUMBER~~
NRL [redacted] 4339 MR (14)

2. GOVT ACCESSION NO.
AD A093643

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
ENVIRONMENTAL CONSTRAINTS IN EARTH-SPACE PROPAGATION. (6)

5. TYPE OF REPORT & PERIOD COVERED (9)
~~Interim report on a continuing NRL problem.~~ memorandum rept.,

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
John M. Goodman (10)

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Research Laboratory
Washington, D.C. 20375

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
61153N
(16) RR03302 44
71-0149-0-0

11. CONTROLLING OFFICE NAME AND ADDRESS
Office of Naval Research
Arlington, Virginia 22217

12. REPORT DATE
(11) 20 Nov[redacted]80

13. NUMBER OF PAGES
55 (12) 51

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This report is based upon a paper by the same title presented at the NATO-AGARD conference on "Propagation Effects in Space/Earth Paths" held in London, England, May 1980.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Environmental effects	Communication satellites
Radiowave propagation	Navigation satellites
Aerospace utilization	Magneto-ionoic effects
DoD mission areas	Tropospheric effects

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The advantages of utilizing space for telecommunications is well known in both the commercial and military arenas. A small complement of satellites at synchronous orbit, for example, may provide nearly global coverage and may be designed to support small disadvantaged customers as well as those characterized by large antenna structures and sophisticated aquisition and processing capabilities. Modern navigational and timing needs can also be satisfied through exploitation of space platforms and NAVSTAR/GPS is a system which exemplifies the utilization of space for those purposes. Applications of space in surveillance and kindred areas

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S/N 0102-LF-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

251950

20. Abstract (Continued)

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This paper reviews the general utilization of space to introduce the importance of earth-space radio propagation with special emphasis directed toward DoD mission areas. An outline of the basic properties of earth-space RF propagation follows and finally an assessment of the major effects is given.

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FNVIRONMENTAL CONSTRAINTS IN EARTH-SPACE PROPAGATION (A REVIEW PAPER)

SUMMARY

The advantages of utilizing space for telecommunications is well known in both the commercial and military arenas. A small complement of satellites at synchronous orbit, for example, may provide nearly global coverage and may be designed to support small disadvantaged customers as well as those characterized by large antenna structures and sophisticated acquisition and processing capabilities. Modern navigational and timing needs can also be satisfied through exploitation of space platforms and NAVSTAR/GPS is a system which exemplifies the utilization of space for those purposes. Applications of space in surveillance and kindred areas also exist and spaceborne instruments for monitoring the exoatmospheric environment and transmissions from the sun abound. There is an obvious charm in the utilization of space for various purposes, however most applications require the transmission of intelligence or data between space platforms and other space segments or a ground terminal. Thus the channel or the propagation path clearly becomes a part of the total system as a perturbation source. The nuisance value of the propagation path derives from the extent to which it does not duplicate free space at a specified frequency.

This paper reviews the general utilization of space to introduce the importance of earth-space radio propagation with special emphasis directed toward DoD mission areas. An outline of the basic properties of earth-space RF propagation follows and finally an assessment of the major effects is given.

1. INTRODUCTION

Since the advent of the space age, there has been an accelerated awareness of the benefits which might accrue from utilization of orbiting systems for a variety of purposes. Because of the unique vantage point provided by space, the potential for military and commercial communication, navigation, surveillance, earth observation, and space research has been increased significantly. Advanced societies have developed the technologies for the successful launch, orbital maintenance, and operation of highly sophisticated systems over the years since 1958; and currently there are more than 800 payloads in orbit of which approximately 30% are still actively performing their assigned missions. Of these, as reported in a popular military journal, approximately 75 are active communication satellites with the majority being Soviet systems [Schemmer, 1978]. These statistics, whether they be precise or not, do indicate the increased emphasis being placed upon space systems by the major industrial nations to fulfill national objectives in the C^3I arena.

In order to fully utilize the benefits of space, it is necessary to account for the subtle environmental factors which may continuously interfere with successful operations or may constrain or limit the performance of the system at seemingly random epochs in time. In principle an a-priori knowledge of the full range of problems imposed by nature should lead to the design of robust systems (including both space segments and earth terminals) which are either impervious to disturbances or those which may adapt to the changes in

Manuscript submitted July 18, 1980

some sense. At the very least the environmental knowledge is a pre-requisite to intelligent system design. Otherwise "band-aid" approaches will be dictated after-the-fact. For the disadvantaged user who is constrained by operational environment, cost, real-estate, or other factors, the entire burden or robustness must be borne by the space segment and this cost may be too large. Techniques of diversity (including frequency, polarization, time or coding, and space) and various resource management schemes involving re-routing and/or gateway scenarios are options which have been explored for mitigation or avoidance of environmental effects. In some cases the implementation of these techniques is either too costly or cumbersome considering the perceived risk.

This paper outlines the various environmental influences on the earth-space path. A brief summary of various systems which use the earth-satellite path is also included to provide the reader with a background of earth-space propagation requirements and a rationale for consideration of this topic.

2. THE UTILIZATION OF SPACE

2.1 Military Satellite Communications Systems

Trans-ionospheric propagation experiments were performed using the moon as a passive reflector of signals as early as 1946 [i.e., PROJECT "DIANA"] and J. H. Trexler of NRL discovered that UHF voice could be successfully bounced off the moon and returned to earth. It is of interest to note that [Browne et al, 1956] in conducting moon-bounce studies, detected the trans-ionospheric Faraday rotation effect, which was used rather comprehensively in succeeding years in conjunction with artificial earth satellites to study the ionospheric electron content. The U. S. Navy subsequently initiated the first regularly operating satellite telecommunication service in 1960 using the moon-bounce technique. It is understood that this system is still in operation by the U. S. Navy.

The first active link experiments were PROJECT SCORE and PROJECT COURIER. Project SCORE, initiated by the U. S. Air Force, culminated in a 1958 launch of an Atlas-ICBM-Type rocket containing communication equipment which allowed for earth reception and retransmission of voice messages. PROJECT COURIER culminated in two satellite launches in 1961. A logical follow-up to the early moon-bounce experiments was the passive communication ECHO satellite in 1960 and the launch of a large cloud of metallic dipoles (PROJECT WEST FORD) by Lincoln Laboratory in 1963. Both of these initiatives would potentially allow for communication service whenever the moon was not in view.

Other early tests were conducted by NASA (viz; TELSTAR in 1962, EARLY BIRD in 1965, and SYNCOM in 1963) and the Soviet Union (i.e., the MOLNIYA series).

The U. S. Dept of Defense recognized the utility of satellites early in the decade of the sixties and the DoD initiated Project ADVENT, a comprehensive program which was subsequently cancelled as too ambitious, and replaced it by the IDSCP (Initial Defense Satellite Communication Project) which was a phased-approach concept. Since that time the DoD has relied increasingly upon satellites for communications, surveillance, and navigation.

Until the Viet Nam War when IDSCP was initiated, all satellite communications systems were funded out of R&D dollars, were simply demonstration systems, and therefore were used very limitedly. Indeed they lacked the suitable follow-on systems to ensure the requisite continuity of service to potential customers. The first SHF demonstrations were performed with the Lincoln Experimental Satellites LES-3 and LES-4 launched in 1965. The IDCSP, relying heavily on earlier U. S. Army participation in the NASA SYNCOM program, launched 26 satellites between 1966 and 1968 [Miller, 1976] for SHF communications (i.e., 7-8 GHz).

The Military Satellite Communications Systems have evolved along two lines; SHF for long-haul, fixed, point-to-point communications, and UHF for tactical communications. The SHF requirements were initially satisfied by the IDCSP and the follow-up system was the Defense Satellite Communications System (DSCSII) which was a larger system with greater power, bandwidth and link connectivity potential. Launches began in 1971 and two satellites are currently in orbit, one over the Pacific and the second over the Atlantic Ocean. The DSCS SHF requirements include long haul communications, and support to WWMCCS for crisis and conflict management, ground mobile forces, large Naval ships and some non-DoD users.

Unfortunately the constraints of terminal cost, size, and complexity required for connectivity with the SHF-based DSCS systems are too severe for many users, especially the small tactical-mobile forces. The U. S. Navy is a prime example of this category of user which has thousands of individual units under its aegis. Hence the 225-400 MHz band (UHF) has been utilized for this large aggregate of users to limit cost and allow utilization of smaller less constraining terminals. Early tests of UHF for telecommunications were performed by MIT Lincoln Lab with the launch of the LES-5 satellites in 1965, followed by LES-6 in 1968. These satellites studied propagation effects among other things and demonstrated the utility of UHF for tactical use. The result of the UHF research lead to the formation of the tri-service Tactical Satellite Program (TACSATCOM). The TACSAT satellite was launched as a result; it had both UHF and SHF capability. Although the TACSAT satellite was successful, it soon emerged that ionospheric scintillation could be a potential problem at UHF [Paulson and Hopkins, 1973]. This was somewhat of a moderate surprise to military designers even though NASA scientists had recognized the potential problem for VHF links somewhat earlier [Golden, 1968] and vigorous work on radio star and satellite beacon scintillation had been undertaken by AFCRL and others for many years previous to the launch of TACSAT. The follow-up to the TACSATCOM program was the two-service UHF satellite communication system called FLTSATCOM. This system contains the U. S. Air Force AFSATCOM subsystem as a separate entity within the main frame while at the same time preserving the identity of a separate UHF satellite for the Fleet. The FLTSATCOM is a major component of the Navy SATCOM program and has several advantages over TACSATCOM including reduced dependence upon OCONUS (Outside Continental United States) facilities, provision for a robust Fleet Broadcast (FLTBCST), a ship-to-shore information exchange system, SHF uplink jamming protection for FLTBCST and UHF downlink to exploit simple, low-cost shipboard equipment. Because of the complexity of the FLTSATCOM system, launch schedule delays were necessitated. As an interim step the U. S. Navy contracted with COMSAT General Corporation to lease UHF service on MARISAT, with 2 satellites being launched in 1976 -- one being placed over the Atlantic and one over the Pacific, these satellites are termed GAPFILLER. Subsequently another satellite was placed over the Indian Ocean. The FLTSATCOM satellites were launched in 1978, 1979, and 1980. As noted above, they provide part of the AFSATCOM strategic command and control (C^2) function. AFSATCOM transponders are also located on other host satellites such as the U. S. Air Force Satellite Data Systems Spacecraft. For the U. S. Navy there are four primary Communication Area Master Stations (CAMS) and one Naval communication station which are configured for GAPFILLER/FLTSATCOM capability. They are Norfolk, Virginia (NAVCAMSLANT), Stockton, California (NAVCOMMSTA), Hawaii (NAVCAMSEASTPAC), Guam (NAVCAMSWESTPAC), and Bagnoli, Italy (NAVCAMSMED). Currently the U. S. Navy has over 416 AN/SSR-1 FLTBCST Receivers and 638 AN/WSC-3 transceivers in place. The United Kingdom and the U. S. participated jointly in the IDCSP test phase and the U. K. and U. S. launched two SKYNET satellites to meet the military needs of the United Kingdom .... specifically long distance point-to-point digital links between Hong Kong and London and selected tactical links [Miller, 1976]. SKYNET I was launched in 1969 and SKYNET II was launched in 1974. The NATO Satellite program was established to improve intra-alliance communications. NATO IIA and IIB were launched in 1970 and 1971, being the same design as SKYNET. NATO IIIA was an evolutionary higher power satellite; the first of three satellites was launched in 1976.

The future Military Satellite Communication System (MILSATCOM) will be comprised of (i) an improved general purpose SHF system (now called DSCS III), (ii) an improved UHF system (now called GPSCS) and (iii) an improved AFSATCOM (now called SSS for Strategic Satellite System). Improvements in the DSCS III will include six identical transponders for user isolation and redundancy, and the use of two independent multibeam antennas with patterns ranging between 3.5° and earth coverage to increase capacity and provide flexible coverage. The GPSCS improvements may include FDMA uplink, a TDM downlink, satellite signal processing, and a large aperture multi-beam antenna. The SSS improvements may include new modulation techniques, satellite-to-satellite cross-link, EHF, and the use of new long-life radioisotope thermoelectric power generation. Some of these ideas have been tested with the LES-8 and LES-9 satellites.

Future generation satellites both in the tactical and strategic arenas may well be designed to operate in the EHF portion of the radio spectrum. There are certain advantages to this including robustness, jam resistance, and increased bandwidth. However the disadvantage lies with higher propagation loss especially during rainfall. According to [Reynolds, 1979] of the U. S. A. F. Space Division, an option for use of SHF/X-Band (i.e. 7-8 GHz) would be included for backup. It is noteworthy that high latitude users may not be too joyful at the prospect of EHF satellites in geostationary orbits because of the low elevation angles resulting in long paths through the atmosphere and enhanced atmospheric absorption. Thus both geostationary and polar orbiting satellites may be required. For connectivity either EHF or laser cross-links between satellites might be explored along with suitably selected earth terminals as gateways [Rosen, 1979].

2.2 Military Navigation Systems

The charm of satellite-borne navigation aids is obvious just as it has been for satellite communications for many years. However until recently the existing ground-based systems have been adequate for most purposes. Emitters in space result in expanded system coverage and the space frequency selection process is limited only by propagation loss and measurement error and not by the vagaries of the frequency-dependent terrestrial propagation path as in OMEGA, LORAN and in HF communication systems. On the other hand local region systems may be less susceptible to interference and jamming.

The only operational satellite-based navigation system is the Navy TRANSIT or NNSS system which has been in operation since 1964 but was fully operational in 1968. It is essentially an all-weather passive user system producing fixes to better than 0.1 n.mi. Timing is synchronized to UTC within 200 microseconds. The constellation consists of 5 satellites in circumpolar orbits at 600 n.mi. and transmitting at 150 and 400 MHz. The position of the user is determined by measuring and examining the doppler shift of the signals. TRANSIT terminals are in use on a variety of Navy platforms including SSN, CV, DD, DE, DLG with the earliest use being for FBM submarines. The accuracy requirements range from 0.1 to 2 km with the former being appropriate for interface with the Shipboard Inertial Navigation System (SINS). The typical terminal consists of an antenna, receivers, processor and display unit. The opportunity for a SATNAV fix is dependent upon the user latitude with intervals being as short as 30 minutes near the poles and as much as 110 minutes near the equator. Over 300 Navy platforms are equipped with TRANSIT terminals.

The Defense Navigation Satellite Time and Ranging System (NAVSTAR) or Global Positioning System is a four service system in which the space segment provides the RF signal, the ground segment provides the satellite ephemeris and clock synchronization, and the user equipment computes position, velocity and time. The attributes of the system are precise 3-D navigation, continuous global coverage, worldwide common grid, passive all-weather operation, high jam resistance, and selective availability [Henderson, 1979]. The total system will comprise 24 satellites with 8 satellites in each of three orbital planes such that each user will have four satellites available within the field of view at any time. There are a myriad of GPS applications. The NAVSTAR program was conceived in the early 70's, the development began in 1974, and full operational capability is scheduled by 1987. The GPS deployment of terminals will consist of at least six categories of equipment to support the varied user environment as well as cost and accuracy requirements. User types may be either ships, aircraft, or manpack. The minimum terminal will consist of an antenna, receivers, data processor, software, control, and display unit. Most users will receive both 1227 and 1575 MHz transmissions but there are also some single frequency users. By the 1990's over 20,000 military users are projected. Of these the U. S. Navy plans approximately 2700 terminals to be installed on submarines, aircraft, and ships [U.S.N. Space Master Plan, 1979]. The advanced GPS will provide 3 meter accuracy for two frequency users. Furthermore it is planned to add special purpose communications and surveillance packages to the GPS. There is some limited concern vis-a-vis environmental effects and GPS. This concern is outlined by [Parkinson et al, 1976] and [Cretcher, 1975].

2.3 Satellites Used for Earth Observations

There has been a continuing evolution of earth monitoring satellites launched since the initial TIROS 1 was launched in 1960. Meteorological studies of significance to long and short-term forecasting have been facilitated since that time and techniques have been developed for global mapping of weather systems and atmospheric phemonomena with a variety of sensors. The groundwork for future earth-observation from space was paved by the early TIROS, NIMBUS, ATS, AND ESSA series of satellites. The current operational weather satellite system spawned by the NIMBUS and TIROS efforts is the ITOS (Improved Tiros Operational System). The prototype spacecraft TIROS-M, launched in 1970, was followed by satellites dubbed NOAA 1-5 to satisfy needs of the U. S. Weather Bureau. The evolution and launch of a series of Geostationary Operational Environmental Satellites (GOES) was based upon the success of the ATS-1 and ATS-2 in demonstrating the benefit of continuous observations. (These are dubbed SMS/GOES). The first of the Synchronous Meterological Satellites (SMS) were launched in 1971 and 1973. Others followed in 1975. The SMS/GOES satellites also monitor solar x-ray flux of benefit to solar physicists, ionosphericists, and communication specialists concerned with sudden ionospheric disturbances caused by solar flares. Current and future operational systems include LANDSAT-C, NIMBUS G, TIROS-N, and SEASAT, the latter being the first satellite designed especially for ocean surveillance - having both active and passive microwave sensors on the same spacecraft and having the ability for global observation and quasi-real time data processing and dissemination. Unfortunately SEASAT operated properly for only a few months following its launch. Some of these future systems will produce daily data rates exceeding 10^{12} bits/day. The NASA Tracking and Data Relay Satellite System (TDRSS) will be employed for data relay. This will obviate the use of a cumbersome set of ground stations for tracking and retransmission to a orbital processing facility for ultimate data dissemination. [Garbacz et al, 1976].

Military requirements vis-a-vis satellite meteorological data have been documented [MJCS, 1976] and are generally applicable to all services in the DoD. Ocean surveillance is stressed in the U. S. Navy as would be expected. Operational polar orbiting satellite systems to fulfill these requirements include the DoD 2-satellite system called the Defense Meteorological Satellite Program (DMSP) and the civilian 2-satellite system (NOAA) developed under the ITOS program discussed previously. The two DMSP satellites are in noon-midnight and dawn-dusk orbits of 845 km respectively. DMSP data is directly available to Air Force and Naval ground terminals and is used to support tactical air, surface, and ASW operations among others. Global synoptic data is also transmitted to the Fleet Numerical Weather Central (FNWC) for use in global weather analysis and forecasting models. DMSP data is transmitted to the Air Force Global Weather Central (AFGWC) for weather analysis, and special sensor data is also used for application in ionospheric modelling, forecasting, and assessment to serve a variety of DoD and civilian customers. Future plans may call for incorporation of an operational topside ionosonde on DMSP to characterize the topside ionosphere to improve the support of various C^3I functions. The NOAA operational satellites are in polar sun-synchronous orbits and at altitudes of approximately 1500 km. Observation times occur near 0900 LT and 2100 LT. U. S. Navy use of the TIROS-N data is also planned in the future; with data being transmitted to FNWC in Monterey, California.

Geosynchronous satellites which provide environmental data to support DoD requirements include those in the GOES System mentioned above. GOES is part of the Worldwide Geosynchronous Meterological Satellite System (WGMS), provides visible and IR data, and has an environmental data relay capability.

There is considerable although not unassailable pressure to merge both civilian and military needs into a single national system for meterological use in the future. The principal justification for a separate military system (such as BLOCK 6 on DMSP) arises from control and security issues and more stringent military requirements.

2.4 Exo-atmospheric Monitoring and Geophysical Forecasting Systems

The U. S. Air Weather Service has responded to the requirements of the U. S. Air Force through a comprehensive development of various categories of support in the space environment arena. The Air Force Global Weather Central (AFGWC) system at Offutt AFB, Nebraska includes a central facility to forecast the state of the sun, the interplanetary medium, the magnetosphere and the ionosphere. The Air Weather Service and the Air Force Geophysics Laboratory have coordinated the establishment of a network of solar optical (SOON) and radio (RSTN) stations to augment the traditional solar monitoring technologies. Other nearly real-time data sets available at AFGWC include x-ray and high energy proton data from GOES, some x-ray and particle data from

VELA 5 and 5B, a variety of data from the NOAA/AWS High Latitude Monitoring Station (HLMS), magnetometer data from its magnetometer data network, auroral imagery, in-situ plasma probe and precipitating electron data from DMSP, and various ground-based ionospheric data including that obtained from vertical incidence ionosonde and total electron content monitors.

The U. S. Navy entered into the quasi-operational exo-atmospheric monitoring arena with the launch of SOLRAD HI in 1976. This system which had severely degraded by 1979, was designed to meet two goals: First, to provide continuous real-time solar measurements to the U. S. Navy during FLEET support demonstrations and to the Air Force and NOAA for their enviromental forecasting centers; and secondly, to provide data for research. The two satellite system, super-synchronous in nature, carrying a multiplicity of particle and electromagnetic sensors, was a central ingredient in a total system for Environmental Prediction and Assessment (EPAS) for predicting performance variations in communication, radar, and navigation systems. The Navy has no current plan to build a follow-on for SOLRAD HI.

2.5 Other Systems and Activities

2.5.1 The Commercial World

There are, of course, a plethora of commercial communication satellites now in operation and many more are planned. Telecommunications is probably the only commercial use of space technology and it is now a multi-billion dollar industry. A review of the industry is provided by [Gould, 1976].

2.5.2 The Scientific World

The ability to study the earth's environment from the vantage point of space has provided answers to many basic questions while raising some new and interesting ones. Of particular note here are the vigorous programs in solar-terrestrial physics which have been conducted since the launch of the first U. S. earth satellite, Explorer I in 1958. Approximately 90 satellites have been involved in solar-terrestrial research. Studies of solar electro-magnetic and particulate flux, solar features such as coronal holes, the solar wind, the interplanetary magnetic field, the radiation belts, and the electron and ionic populations in the outer atmosphere are just a few noteworthy examples. Satellites have been platforms for synoptic measurements of the ionosphere through use of various in-situ probes and other techniques which exploit the unique properties associated with radio-wave propagation in an inhomogeneous magneto-ionic medium. Topside ionosonde which operates in the HF band (Canadian Alouette and ISIS spacecraft and the Japanese ISS-B satellite) have provided considerable information about the macroscopic morphology of the topside ionosphere and the F2 maximum whereas direct measurements of electron density (in-situ probes) have been used to deduce inhomogeneity wave number spectra, a parameter of importance in scintillation theory. A number of satellites not specifically designed for scientific use have nevertheless provided a resource by which useful data has been obtained. These include many communication satellites as well as experimental satellites of opportunity. Of particular interest are total electron content studies based upon measurements of the dispersive doppler or Faraday rotation introduced by the ionosphere on the downlinks of various space systems. These data are ultimately of importance to the NAVSTAR/GPS community. Communication satellites are the primary source of amplitude scintillation data; however the necessity to understand the importance of phase scintillation in the operation of advanced communication systems using PSK modulation or its derivatives has led to the launching of a satellite designed to explore this problem (WIDEBAND DNA-002).

Various experimental studies of millimeter wave propagation have been facilitated through use of Applications Technology Satellites (ATS-5/6), the Communications Technology Satellite (CTS), COMSTAR, and SIRIO.

2.6 Concluding Remarks to this Section

Clearly the utilization of space is increasing for a variety of purposes serving both the civilian and military communities. Because of this, the intervening environment (including the troposphere and its weather, the ionosphere, the magnetosphere, and the interplanetary medium) is a necessary consideration. As a result, serious basic research efforts have been initiated over the years to ascertain the basic nature of the total environment or at least its statistical climatology with the ultimate goal being to estimate the range and variance of deleterious system effects. This information is utilized for purposes of system design and development but may also be of value in developing forecasting and assessment techniques for use in operational resource management. The next section will outline some of the constraints placed upon space systems which rely upon the earth-space propagation path.

3. A RESUME OF EARTH-SPACE RADIO PROPAGATION EFFECTS

3.1 Introduction

One of the earlier papers dealing with this topic was due to Millman [1965] who surveyed both tropospheric and ionospheric effects on radio propagation between the earth and space vehicles. A basic paper with special emphasis on the ionospheric aspect of earth-space propagation by Lawrence et al [1964] is also noteworthy although the more recent developments in scintillation morphology have rendered it considerably outdated in that specialty. For background the reader is referred to books by Davies [1965], Kelso [1964], and Buddin [1964] to name a few, and to the excellent library of AGARD publications which have treated various propagation effects over the years. With respect to propagation effects due to the lower atmosphere, texts by Kerr [1951], Battan [1959], and Bean and Dutton [1966] are good introductions. There are numerous papers which have been published over the years dealing with the material covered in this survey. Nevertheless recent papers by Rush [1979] on ionospheric radio propagation, Klobuchar [1977, 1978] on ionospheric time delay, Aarons [1978] on scintillation morphology, Fremouw and Rino [1978] on scintillation modelling and statistics, Crane [1977] on prediction of rainfall effects and Bean and Dutton [1976] as well as Bothias [1976] on tropospheric propagation are worthy of note. A sketch of the ionospheric effects upon earth-space propagation is also available in a CCIR report [1974]. The proceedings of the two previous IES symposia [Goodman, 1975, 1978] and a recent COSPAR symposium [Mendillo, 1976] are also drawn upon in developing the material for this survey. In the section dealing with millimeter wave propagation and hydrometeor effects, the author was fortunate to have lecture material provided by Ippolito [1975].

There are a myriad of radio propagation effects which come to mind as one recalls the nature of media through which rays must propagate between earth and space. The obvious effects of refraction and absorption in the lower atmosphere have their counterparts in the ionized upper atmosphere but there is a greater richness of effects in the ionosphere as a result of the magnetoionic medium. The Faraday rotation of linearly polarized radiowaves and various differential effects resulting from bi-refringence come to mind. Although tropospheric weather (and the propagation effects it generates) is not uncomplicated, the traditional primary concern vis-a-vis earth-space propagation has been the ionosphere and its personality. This is a result primarily of the fact that space frequencies were lower near the advent of the space age than they are at present or will likely be in the future. The following sections discuss some of the more important RF propagation effects for rays which traverse both the troposphere and the ionosphere.

3.2 Refraction in Earth-Space Propagation

Figure 1 depicts both the tropospheric and ionospheric components of bending introduced over an earth-space path. This is due, of course, to the non-vanishing refractivity in the earth-space medium. The earth-space refractivity may be written

$$N(s) = (n-1) \times 10^6 = N_t + N_I$$

$$= \frac{77.6}{T(s)} \left[p(s) + \frac{4810\,\epsilon(s)}{T(s)} \right] - \frac{40.28 \times 10^{-6}}{f^2} N_e(s) \qquad (1)$$

where N(s) is the refractivity, n is the refractive index, N_T is the tropospheric component or refractivity, N_I is the ionospheric component of refractivity, T(s) is the air temperature (^oK), p(s) is the atmospheric pressure (mb), $\epsilon(s)$ is the partial vapor pressure (mb), f is the radiofrequency (MHz), N_e is the electron density (M^{-3}), and s is the distance parameter.

Figure 2 depicts a typical refractivity profile from ground level through the ionosphere. It is noteworthy that $N_t(h)$, where h replaces s for zenithal propagation, is independent of f whereas $N_I(h)$ is inversely proportional to the square of it. Clearly for the higher space frequencies the tropospheric refractivity dominates the ionospheric component. The immediate implication that ionospheric refractivity effects are to be ignored at higher space frequencies is to be avoided, however.

With respect to gross tropospheric bending Bean and McGavin [1965], Bean and Cahoon [1957], and Bean et al [1971] have shown that surface values of the refractivity N may be used to approximate the effect. A considerable amount of work has been done by Bean and his colleagues as well as others in recent years. For example the reader should examine material in the NATO/AGARD conference on Tropospheric Radiowave Propagation [Albrecht, 1971] in which a review by Millman [1971] is contained (Also see Bean and Dutton [1976] and Bothias [1976]). Bending through the total neutral atmosphere may be given by the following approximate relation [Bean and McGavin, 1965]:

$$\tau_{\infty}(\theta) = b(\theta)\, N_s + a(\theta) \tag{2}$$

where θ is the initial ray elevation angle, N_s is the surface refractivity, and a and b are constants.

A typical value for N_s is the order of 334 and the set (a,b) ranges between (-18.0, 0.12) at $\theta = 0^{\circ}$ and (-0.14, 0.01) at $\theta = 6^{\circ}$. The refraction at these extremes amounts to 21 and 3 milliradians respectively. Figure 3 from Bean and McGavin [1965] exhibits the θ dependence of τ_{∞} and its standard deviation. It is noteworthy that there does exist a climatology for the surface refractivity and models for $N_s(h)$ also have been published (See Bean and Dutton [1976]). The simple recipe given by equation 2 above is obviously insufficient under extreme climatic conditions, and in particular the "humid" term (i.e., 4810 ϵ/T) exhibits large variations. It is well known that both the horizontal and vertical details of refractivity are of great importance in radio propagation. If the vertical gradient of N has a very large negative value (for example $\leq$ - 157 N units per km), then super refraction or ducting will occur. If the vertical gradient in positive (or slightly negative), then super refraction will occur. Such matters, however, are generally of little significance to earth-space links except at very low propagation angles. It is clear from this discussion and also from Figure 2 that the refractivity of the atmosphere is not a pure exponential. Attempts have been made to construct both 2-part and 3-part exponential models [Bean et al, 1966]. Even these sophisticated models are inadequate to explain the situation in the tradewind zones.

The index of refraction is the troposphere is greater than unity and since dN/dh is negative in that region, non-zenithal rays are bent away from the normal. As a result, the apparent elevation to the space object is higher than its actual value and the radio range to the object is larger than the geometrical distance. The index of refraction in the ionosphere is less than unity. Nevertheless, the net effect of the ionospheric component of refraction is to combine with the tropospheric contribution such that the total refraction is essentially the sum of the two components. Figure 4 [Millman, 1965] shows the total refraction error introduced at radio frequencies of 100 and 200 MHz as a function of altitude. Limiting tropospheric and ionospheric range errors due to refraction and signal delay are given in Figure 5 as a function of elevation angle. It is noteworthy that the time delay component of range error dominates for elevation angles above 3°. The diurnal variation of the ionospheric component of elevation error at 400 MHz is given in Figure 6 [Evans and Wand, 1975], and Figure 7 shows that the ratio of refractive error to range error is not fixed as a function of local time. Of course the range error results from both a time delay due to an increase in path length (caused by bending) and to a reduction in the radiowave signal velocity, so such behavior is not unanticipated.

In summary we may state that the ionospheric component of refractivity remains quite important in comparison to the tropospheric component in the UHF band provided the elevation angle exceeds a critical value, say 5°. Below this elevation the tropospheric component begins to dominate and other effects such as ducting, atmospheric multi-path, and atmospheric scintillation become increasingly important. Millman [1971] reviews many of these effects. The tropospheric errors are typically less variable at higher elevation angles and the climatology of surface refractivity and its variance exhibits a degree of stability (or may be readily measured). As a result, routine subtraction of the tropospheric effects of bending and range bias may be accomplished with some degree of confidence. Ionospheric errors are not as easy to address since the climatology is not well known and the variances are relatively large and moderately unpredictable. This situation still exists despite the fact that valiant attempts at ionospheric prediction and assessment continue to this day.

3.3 Attenuation in Earth Space Paths

The absorption introduced by the ionosphere is of negligible significance at UHF and higher space frequencies. The most enhanced effects would be introduced during polar cap absorption (PCA) and kindred auroral events. At UHF even these extreme events will produce absorption of less than 1 dB at space frequencies above VHF. The interested reader is referred to AGARDOGRAPH No. 53 [Gerson, 1962], Davies [1965], and CCIR Report 263-3 [1974].

The troposphere on the other hand introduces potentially severe attenuation of earth-space signals. Attenuation, including both absorption and scattering, is considerably a function on the various atmospheric constituents and their frequency-dependent characteristics. Figure 8 [Bern, 1979] depicts the specific attenuation for normal absorption, resonance absorption, rain, and fog. Absorption and scattering are typically unimportant for frequencies less than 3 GHz. Figure 9 shows the total attenuation through the atmosphere due to resonance absorption for an elevation angle of 45°. Note that at 61, 119, 183, and 324 GHz the attenuation exceeds 100 dB. Scattering from clouds and hydrometers (rain) will reduce the amount of energy available in the forward direction, will change the polarization of the radiowaves, and will defleet energy back toward the transmitter as well as other directions.

Probably since the resonance absorption peaks of H_2O and O_2 are well *known and can be avoided*, the most significant future problem for systems which will use the earth-space propagation path at frequencies between 10 and 100 GHz is likely to be rainfall attenuation. Two types of rain are considered: stratiform and convective. Stratiform rain generally develops in stable masses of air, along frontal surfaces typically, and is characterized by steady and uniform rain over wide areas for hours to days; low rain rates are typical. Convective rainstorms, on the other hand, develop in highly unstable air masses, are limited in extent and duration and are characterized by high rain rates. If rainfall statistics are unavailable for a typical area, it is possible to estimate the rainfall distribution from Figures 10 and 11 due to Bean and Dutton [1976]. Attenuation by hydrometers is given by

$$\alpha\,(\mathrm{dB/km}) = 4.343 \int_0^{\infty} Q_T(a)\ \eta\ (a,R)\,da \qquad (3)$$

where Q_T is the attenuation cross section/drop,
η is the drop size distribution, a is the drop radius,
and R is the rain rate.

The attenuation function Q_T is determined from classical Mie and/or Rayleigh scattering theory and for computing α several drop size distributions are available [Laws and Parsons, 1943; Marshall and Palmer, 1948; and Joss et al, 1968]. From the Laws & Parsons distribution, the specific attenuation is given in Figure 12 for various rain rates. An empirical relationship between rain rate R and α is due to Ryde and Ryde [1968], and Gunn and East [1954]:

$$\alpha\,(\mathrm{dB/km}) = a\ R^b \qquad (4)$$

where a, b are frequency dependent constants.

Curves of the parameters a and b are given in Figure 13 (Beach [1979]). Uniform rain attenuation is proportional to the cosecant of the ray elevation angle since the total attenuation is proportional to the product of the specific attenuation α and the path length L.

The frequency scaling law for rainfall attenuation is approximately.

$$\frac{A(f_2)}{A(f_2)} = \left(\frac{f_2}{f_1}\right)^{1.72} \qquad (5)$$

which for uniform rain becomes approximately a_2/a_1.

It may be shown that water cloud attenuation is equivalent to light rain ($\leq$ 5 mm/Hr) attenuation below 100 GHz. Ice cloud attenuation is at least 2 orders of magnetude less than water cloud attenuation and thus is of little relative practical significance. Figure 14 exhibits cloud attenuation as a function of frequency.

3.4 Polarization Effects in Earth-Space Paths

The Faraday effect is well known to ionosphericists since it is a major technique for measuring the total electron content of the ionosphere. The expression for the amount of Faraday rotation is given by:

$$\Omega = 2.97 \times 10^{-2}\, f^{-2} \int H \cos\theta \sec\chi \ N dh \qquad (6)$$

where Ω is the amount of rotation of the plane of polarization (radians), f is the radiofrequency (Hz), H is the magnetic field strength (Amperes turns/meter), χ is the ray zenith angle, N is the electron density (#/m^3) and h is the vertical distance.

Due to the inverse f^2 dependence of Ω, the amount of Faraday rotation diminishes rapidly as the space frequency is raised. At 7 GHz, for example, the plane of polarization of the transmitted signal would rotate only 1.4 degrees in transit through the entire ionosphere assuming a value for $\int Ndh$ of 10^{18} electrons/m^2 and $H \cos\theta \sec\chi = 40$ amperes turns/meter. Below 1 GHZ the amount of rotation begins to become significant and circularly polarized antennas are employed to obviate the effect. However this mitigation scheme disallows the use of polarization as a means for frequency re-use.

The major factors in the transmission path causing depolarization effects are hydrometeors, multi-path, and Faraday rotation. Of these three, the depolarization caused by rain dominates decisively at GHz frequencies. It has been experimentally shown that the polarization isolation is inversely proportional to the signal attenuation (See Figure 15). Ice depolarization also occurs but is less significant.

3.5 Propagation Delay in Earth-Space Propagation Paths

The total excess delay ΔT for a signal traversing an earth-space path has two additive components, tropospheric and ionospheric. Thus:

$$\Delta T = \Delta T_t + \Delta T_i = \frac{10^{-6}}{c} \int_o^S N_t(s)ds + \frac{40.3}{cf^2} \int_o^S N_e ds \qquad (7)$$

where c is the free space velocity of light, N_t is the tropospheric refractivity $(n-1) \times 10^6$, f is the radiofrequency, N_e is the electron density, s is the distance along the ray trajectory, and the integral $\int_o^S N_e ds$ is the total electron content (TEC) of the ionosphere.

The first term ΔT_t is approximated by N_s H sec χ where N_s is the surface refractivity, H is the atmospheric scale height and χ is the ray zenith angle. Taking $N_s = 300$ and $H = 7 \times 10^3$ meters, we see that ΔT_t is the order of 7 nanoseconds. This term may be easily modelled to leave a residual of less than 1.5 nanoseconds. The second term ΔT_i is dependent upon frequency. At the GPS frequency of 1.6 GHz, and taking the integral equal to 10^{18} electrons/m^2, we find that $\Delta T_i = 50$ nanoseconds. There is, of course, a considerable variation in this number because of the extreme variability in the total electron content, TEC. Using various models for prediction of ΔT_i residuals of between 1 and 13 nanoseconds have been observed [Parkinson et al, 1977]. Various models have been used to predict the TEC [Klobuchar and Allen, 1970; Waldman and daRosa, 1971; Rao et al, 1971; Pisacane et al, 1972; and Bent et al, 1972]. Of particlar interest is a model described by Klobuchar [1977] which predicts the time delay for single frequency users of the NAVSTAR/GPS system. It is written as

$$\Delta T_i = DC + A \cos \frac{(t-\phi)2\pi}{P} \tag{8}$$

where DC, A, ϕ, and P are parameters which are modelled. The functional dependence of the parameters are given in Figure 16.

In general the ionospheric contribution to time delay is compensated for through use of a two-frequency correction technique intrinsic to the GPS system. Thus only single frequency users need to have concerned with the ionospheric contributions to path delay. It will be seen shortly that by far the most important propagation effect as far as GPS is concerned is not propagation delay but scintillation.

In addition to a delay in the mean arrival time ΔT and the well-known pulse distortion effect T_1 [Wong et al, 1978], inhomogeneities in the ionospheric plasma give rise to a time delay spread of the radiowave signal (denoted by T_2). The time delay spread is directly related to angular scattering. In general the time required for a signal to traverse a distance s is given by:

$$T = \frac{1}{c} \int_o^s ds + \Delta T_t + \Delta T_i + T_1 + T_2 \tag{9}$$

where ΔT_t and ΔT_i are the delays due to propagation through the troposphere and ionosphere respectively T_1 is due to pulse distortion arising from finite signal bandwidth, T_2 is due to scattering, and $C^{-1} \int ds$ is the free space transit time.

The term ΔT_i has been described previously (see equation 7); it is obviously first order. The term T_1 arises due to the different speeds in which the various Fourier components of the signal travel [See Figure 40, 41 in Millman, 1965]. The term T_2 is due to scattering from ionospheric turbulence. Figure 17 shows the relationship between the two.

3.6 Scintillation in Earth-Space Propagation

Fluctuations in signal power and phase often accompany radio wave propagation over earth-space paths as a result of inhomogeneties in the refractivity. This phenomenon, analogous to the twinkling of stars in the visible part of the electromagnetic spectrum, has been the object of research for several decades. Many excellent papers are available on ionospheric scintillation and the limited space provided herein does not allow the author to do justice to this extremely rich and interesting phenomenon. Nevertheless scintillation is probably the single most important deleterious factor in future systems utilizing the earth-space propagation path. Much experimental work has been conducted by Aarons and his coworkers at AFGL over the years and he has recently published a short summary of ionospheric scintillation which will serve as a good starting point for the uninitiated [Aarons, 1978]. A thorough review has been presented by Crane [1974]. The morphology of ionospheric scintillation, which is of major interest here, is now fairly well established although details remain to be clarified. A considerable amount of effort has been directed toward the development of models to describe the effect, ultimately directed toward communication channel modelling. In such approach has been to deduce the morphology from all available scintillation data and to derive the channel properties from the hypothesis of a two component signal statistical model [Fremouw and Rino, 1978]. Alternate schemes for modelling the scintillation morphology based upon strong tendencies for correlation with Spread F [Singleton, 1979a, 1979b] or upon the nature of the observed inhomogeneity wave number spectrum have also been suggested [Basu and Basu, 1976, 1979]. Figure 18 shows the scintillation index in the Pacific zone at 257 MHz based upon Singleton's model. Figure 19 is a sample set of scintillation contours obtained using OGO-6 in-situ irregularity data [Basu and Basu, 1979].

Much of the current attention is directed toward the scintillation cause and effect relationships both in the auroral and the equatorial zones. However, more emphasis is placed on the latter zone where the effect is most intense. Indeed GHz scintillation over very limited regions may sometimes occur following ionospheric sunset near the geomagnetic equator. The most interesting aspects of the current drive to understand the problem stems from the involvement of three seemingly distinct phenomena; viz, radar backscatter of small scale structures, scintillation caused by ionospheric inhomogeneities, and detection of quite large-scale electron content depletions or plumes. Clearly the instabilities which give rise to plume development is of major concern in understanding the equatorial scintillation problem. Moreover the scintillation which exists at high latitudes is thought to arise from an entirely different instability and the modest scintillation which occurs at midlatitudes has not been fully investigated. Although plumes as such are not observed at high latitudes, large variations in TEC are at least circumstantially related to auroral zone scintillation since scintillation enhancements are conspicuous in the data only when the TEC gradient is exceedingly sharp [Rino, 1979]. A considerable advance in the total understanding of the ionospheric scintillation phenomenology as well as the underlying physical processes involved has been achieved through utilization of data sets (both amplitude and phase) obtained via the WIDEBAND DNA-002 program. It is well known that external factors related to sunspot activity strongly control ionospheric scintillation occurrence and amplitude. Solar activity tends to enhance equatorial scintillation and geomagnetic activity enhances scintillation near the auroral zone.

A considerable effort has been directed toward the elucidation of those parameters of importance to the design of systems which use the earth-space path in order to counter the scintillation problem. Fluctuations in signal power are a major problem to satellite links in the military band (225-400 MHz) unless compensating techniques are implemented. Communication systems may counter the effects of substantial fading by using space diversity. If the paths are of sufficient separation (depending upon the details of the inhomogeneity wave number number spectrum) then fading is independent on the two links and diversity gain may be achieved. Separation of the order of a kilometer are involved and these useful minimum separations are certainly larger than ship dimensions at UHF [Paulson and Hopkins, 1973]. One would normally expect that radio links which are sufficiently separated in frequency, polarization, or transmission time would be effective in combating scintillation. Alas, this is not true in the case of polarization diversity, and furthermore frequency separation of up to 100 MHz may be required to obtain an adequate diversity gain. Clearly frequency diversity is not applicable in the UHF band but it may be applicable at higher frequencies where allocation problems are less severe. Consequently time diversity is the only viable procedure for overcoming scintillation at UHF. Coding and interleaving schemes have been investigated by Bucher [1975], White [1977], and Johnson [1975]. A study of ionospheric scintillation and its effect on the UHF Fleetbroadcast of FLEETSATCOM [APL Report, 1976] found that without any mitigation schemes employed

- (i) high latitude (i.e., Norwegian Sea) scintillation will distort message traffic up to 5% of the time.
- (ii) message traffic at midlatitudes will only rarely be distorted.
- (iii) equatorial (South and Central Pacific, South Atlantic, and Indian Ocean) scintillation will distort message traffic as much as 30% of the time following sunset and before midnight.

Alternative mitigation or avoidance schemes besides brute force (increasing antenna gain or transmitter power on the uplink or downlink as appropriate) include utilization of DSCS assets at 7-8 GHz for FLEETBROADCAST. This involves the reception of UHF FLTBROADCAST by specified gateway stations that are also equipped with DSCS terminals. These gateways would be located adjacent to virulent scintillation zones but not within the zone themselves. Retransmission of the FLEETBROADCAST to assets in the scintillation zone would be accomplished via DSCS at 7-8 GHz where it is suspected that scintillation is not as severe. It is remarked, however, that selection of the gateway stations is rather a critical function of the known (presumed) morphology of scintillation, and the absence of GHz scintillation in the equatorial zone is by no means clear [Craft and Westerlund, 1972].

In practical terms the most important parameters needed for channel specification include S_4 (the scintillation index), T_c (the fade coherence time), and a rough measure of the coherence bandwidth [Transionospheric Propagation W G Report, 1979]. The fade coherence time must, of course, be large compared to the baud duration to avoid failure; nevertheless as T_c decreases the "time diversity coding gain" will typically increase until the baud duration limit is reached. In this regime the S_4 index is appropriate to the Nakagami [1960] distribution which describes the probability of amplitude scintillation adequately. As a result, fading depth statistics can be deduced with a degree of confidence knowing S_4 alone. Further, the system degradation introduced by S_4 can be retrieved through time diversity albeit with some loss in timeliness and throughput. Clearly in a Rayleigh fading environment (i.e. $S_4 = 1$) the scintillation is characterized as "strong" and pulse distortion may arise in some instances given the conditions above. It is of interest to note that a precise description of the channel using complex signal statistics (i.e. amplitude phase) is unnecessary unless the fading is rapid and strong. But in this instance the Rayleigh model, which is well known and understood, may be employed. When $S_4 = 1$ only a measure of T_c is needed to specify the performance of a communication channel.

There is presently an increased interest in utilizing the earth-space path to transmit increasingly higher data rates and as mentioned above, scintillation conditions in some instances may not support such a requirement. Furthermore the need for greater accuracy and availability of precise navigation data only emphasizes the constraint placed on systems by ionospheric inhomogeneities. Techniques for synthesizing large antennas in space by coherent processing and for improving the detection range of space surveillance radars by coherent detection rely heavily on ionospheric smoothness at the frequency involved. Thus the temporal and spatial personality of inhomogeneities in the ionosphere (and the phase and amplitude scintillation which results) is of utmost relevance. The ionospheric limitation to coherent integration in transionospheric radars has been discussed by Rino et al [1978]. These authors find that the time variation of signal phase is given by

$$\phi(t) = \phi_o + w\,(t-t_o) + \dot{w}\,(t-t_o)^2 + \delta\phi\,(t-t_o) \qquad (10)$$

which is defined over a short interval ($t_o \le t \le t_o+T$) and $\delta\phi$ is a random component of phase defined by a power law probability density function.

The ϕ_o term is a phase bias due to TEC, the linear term $w(t-t_o)$ is the doppler shift (which causes no problem for target coherent detection), and $\dot{w}(t-t_o)^2$ gives rise to spectral broadening and may reduce processing gain as will the term $\delta\phi$ $(t-t_o)$. For midnight periods both $\dot{w}$ and $\delta\phi$ are quite large over the equator limiting integration at VHF to much less than 10 seconds. More striking is that omnipresent non-vanishing $\dot{w}$ values during the day will limit integration to less than a minute. (See Figure 20).

Tropospheric scintillation is also observed in both a clear air and cloudy environment. However the depth of fading is typically less pronounced than ionospheric scintillation observed at lower frequencies. Ionospheric amplitude and phase scintillation diminishes in proportion to $f^{-1.5}$ and f^{-1} respectively, but tropospheric scintillation exhibits little resolvable frequency dependence [Hodge et al, 1976].

Both ionospheric and tropospheric scintillation increase as the zenith angle increases; nevertheless it is found that the obliquity factor for the tropospheric variety of scintillation is much more severe. Near the horizon, tropospheric scintillation will dominate at most earth-space frequencies except under the more virulent conditions. The variance of scintillation (scintillation index) is found to be proportional to $L^{11/6}$ where L is the tropospheric path length. Scintillation as high as 25 dB has been observed at elevation angles of 2^o in the 20-30 GHz band [Hodge et al, 1976].

3.7 Doppler Frequency and the Earth-Space Path

The well known expression for ionospheric excess doppler (Hz) is:

$$\Delta f = -\frac{40 \times 10^6}{cf}\,\frac{d}{dt}\int N_e\,ds \qquad (11)$$

where f is the transmission radio frequency c is the speed of light, and N_e is the electron density.

This number is typically negligible in comparison with the free-space doppler introduced by satellite or target motion.

For geosynchronous satellites, the Δf correction to the transmisson frequency is only academic (being only a fraction of a Hertz) and even for orbiting satellites Δf is relatively unimportant at typical space frequencies. Maximum value of the time derivative occurs near the horizon. Even in this extreme case and for $\int N_e ds = 10^{18}$ electrons/m^2, Δf will be less than 5 Hz at 1.6 GHz. Typically well-designed ϕ lock tracking loops will encounter no difficulty. Even though the dispersive doppler introduced by the ionosphere is not significant as a system effect in earth-space propagation, it has been quite useful in ionospheric studies.

4. CONCLUSION

There are numerous applications for utilization of space in the arenas of communication, navigation, surveillance and related disciplines. The one unique advantage afforded by space is the vantage point it provides. A single satellite, appropriately placed in geosynchronous orbit, can observe and/or serve almost 1/2 the globe. The trend in DoD is for satellite platforms to be the backbone for most strategic and tactical communications, navigation, positioning and overhead surveillance. The virtues of satellites for use in commercial communication and remote sensing of earth resources, weather systems, ocean environment and related areas is well known. Furthermore the use of satellites for relay of data from earth terminals, buoys, and other satellites is of major significance.

Despite the trend toward increased utilization of space, there must be a parallel awareness that over-zealous committment will not ultimately be an Achilles heel. Factors such as survivability in a strategic environment are being studied since they are obvious considerations. However, system architects should also be aware of the environmental constraints which the use of space will necessarily introduce. The ionospheric parameters of importance in space system design are known but their detailed personalities are not completely understood and most certainly forecasting capability is almost non-existent. Typically ad-hoc climatologies are employed to define the ranges (i.e. margins) over which systems must be made to adapt. Thus ionospheric and tropospheric research has been of great benefit to system designers in specifying to first order the degree of robustness which must be engineered into space systems. Futher design constraint reductions would be achieved through use of second order improvements involving some form of environmental monitoring or assessment function. Increasingly the point of view is emerging that the short-term forecasting requirement must be achieved through quasi-real-time environmental remote sensing which is employed in conjunction with algorithms for extrapolation into denied areas.

Not to be ignored is the examination of environmental limitations to earth-space propagation in that such limitations apply to both adversary as well as friendly forces. It is not inconceivable that techniques for exploitation and/or control of the environment may well be components in the hierarchy of future electronic warfare systems. Of special interest in this regard are emerging studies of ionospheric modification using chemical reagents and RF heating. Natural disturbances also have morphologies which might also be exploited although current capability to forecast natural events is probably insufficient. With the increased demands placed upon space systems in terms of accuracy and data rate, the environmental constraints upon the earth-space path may well be a limiting factor in the ability to achieve the design goals. The successful search for "windows" or "doors" in which environmental constraints exhibit extremes should enable enhanced operation in both natural and disturbed environments and more secure operation against a threat. To the extent that natural "doors" and "windows" are non-existent, their creation may be critical and more than justifies continued research in the arena of environmental modification.

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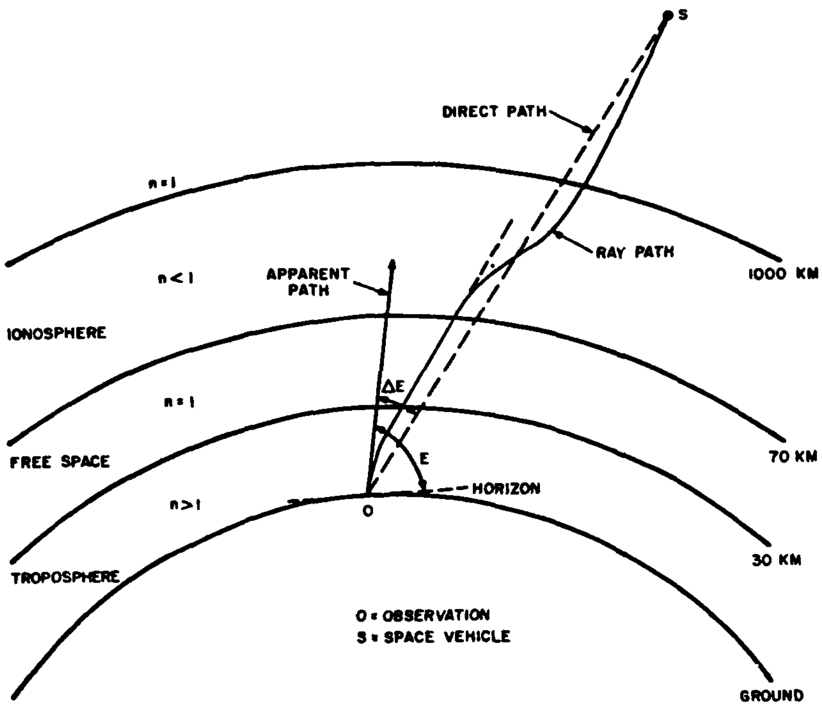

Fig. 1 — Radiowave Trajectory through the Troposphere and Ionosphere. (After Millman [1965])

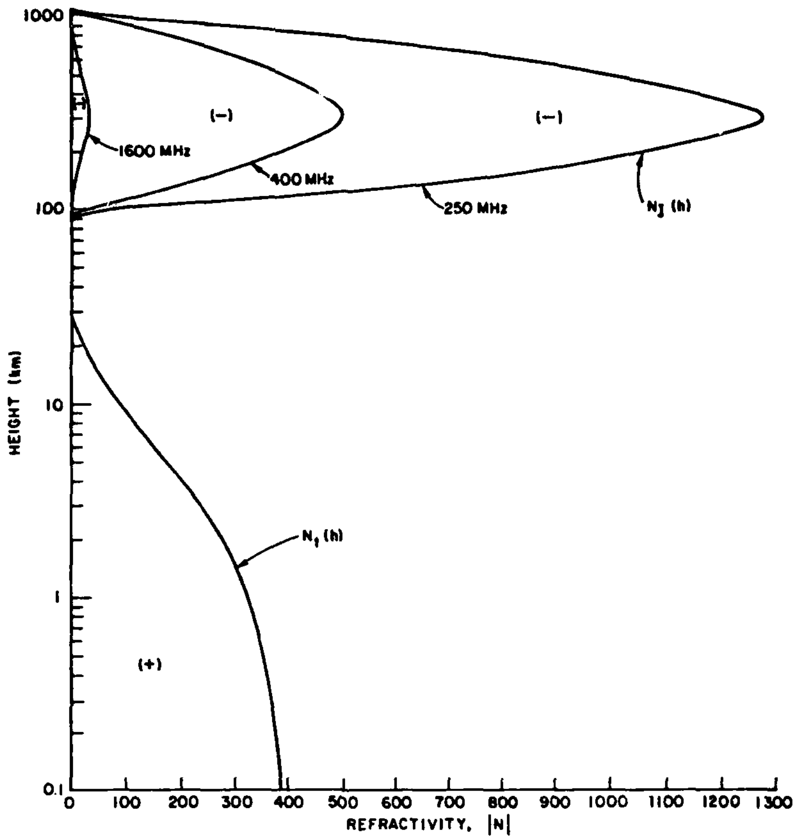

Fig. 2 — Radio refractivity versus altitude. Representative ionosphere profiles are shown for 250, 400, and 1600 MHz. The tropospheric refractivity profile is based on data from Bean et al [1971].

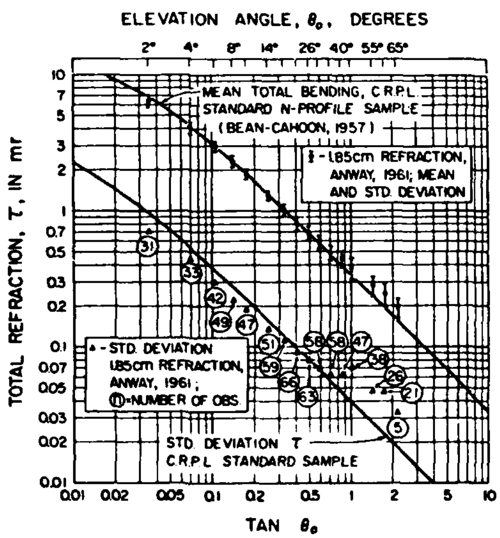

Fig. 3 — Total atmospheric refraction τ and its standard deviation Δ versus elevation angle θ_O. Also shown is a comparison with actual measurements at a radio wavelength of 1.85 cm (16.2 GHz). (From Bean and McGavin [1965])

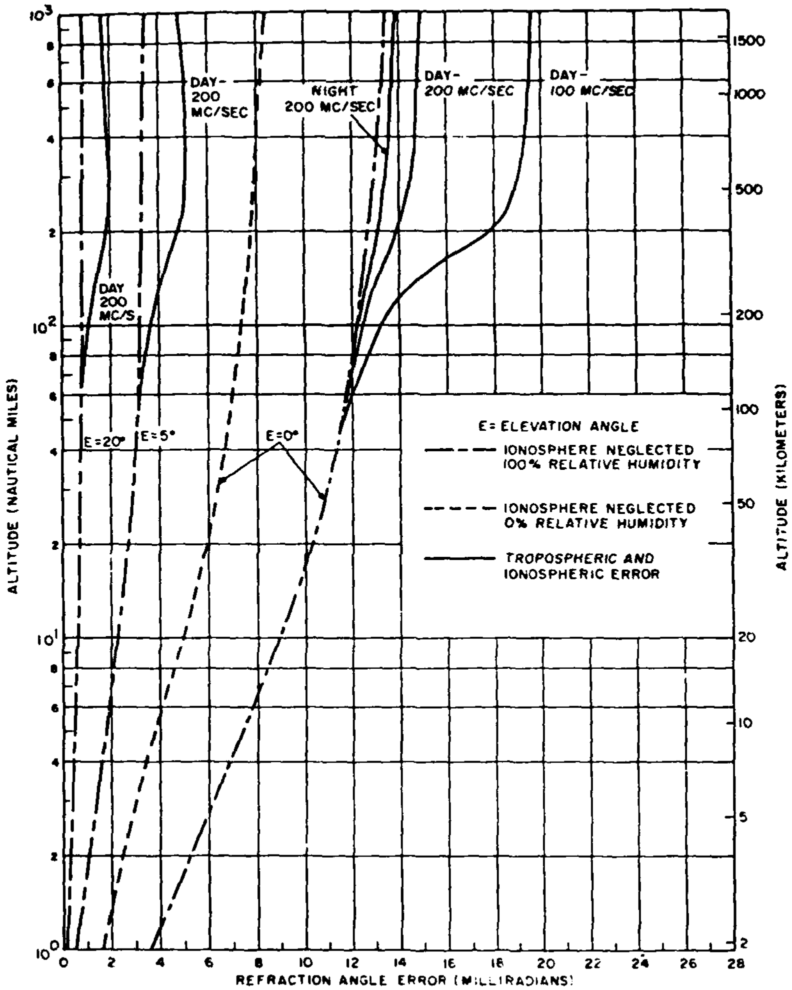

Fig. 4 — Total refraction error at 100 and 200 MHz as a function of altitude. (From Millman [1965])

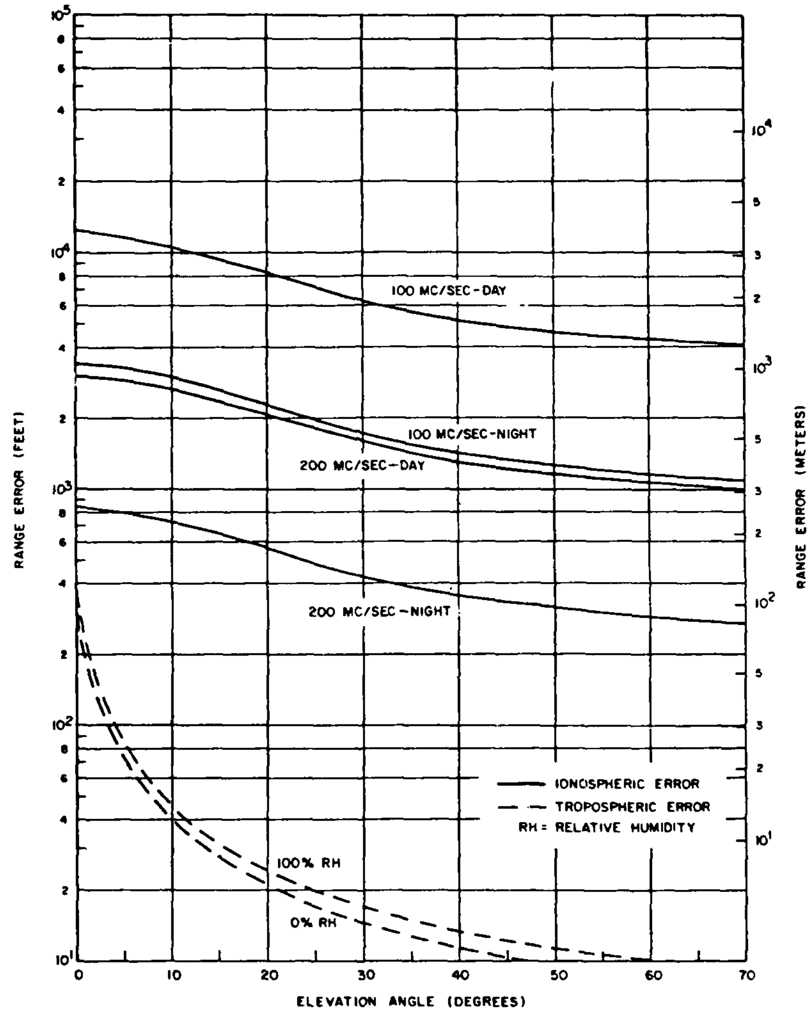

Fig. 5 — Limiting tropospheric and ionospheric range error as a function of elevation angle. (From Millman [1965])

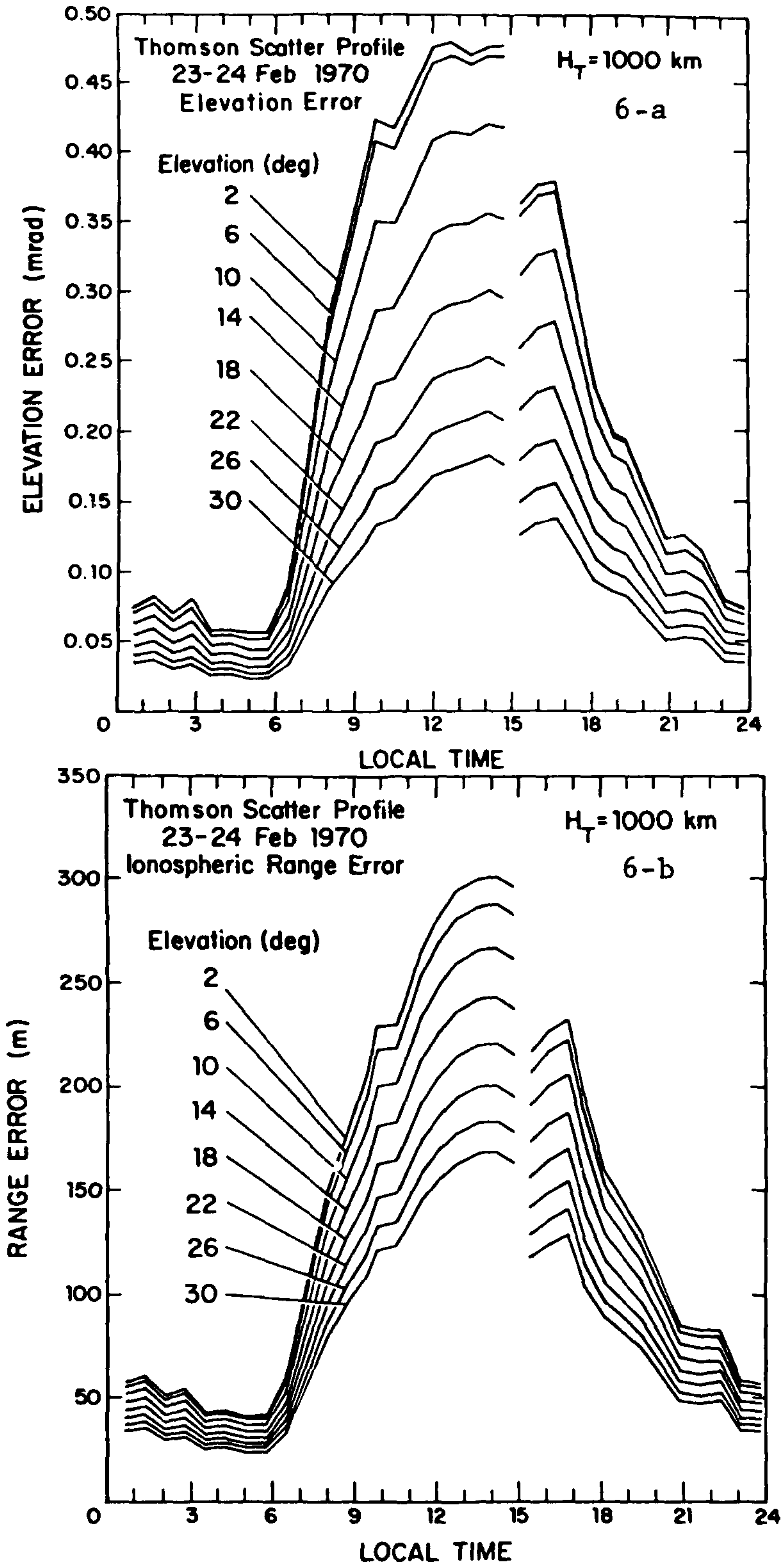

Fig. 6 — Ionospheric refraction (a) and range (b) errors at 400 MHz as deduced by ray tracing through Thomson scatter — derived electron density profiles. (From Evans and Wanu [1975])

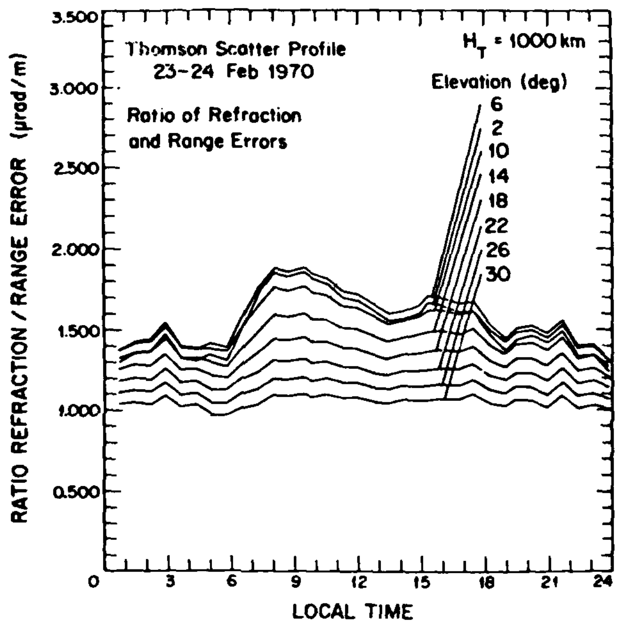

Fig. 7 — Ratio of elevation angle to range error at 400 MHz (from Evans and Wand [1975]). Note that the ratio becomes more linear as the launch elevation angle is increased indicating a reduction in delay due to bending. The bending enhancement in range error is most pronounced at sunrise.

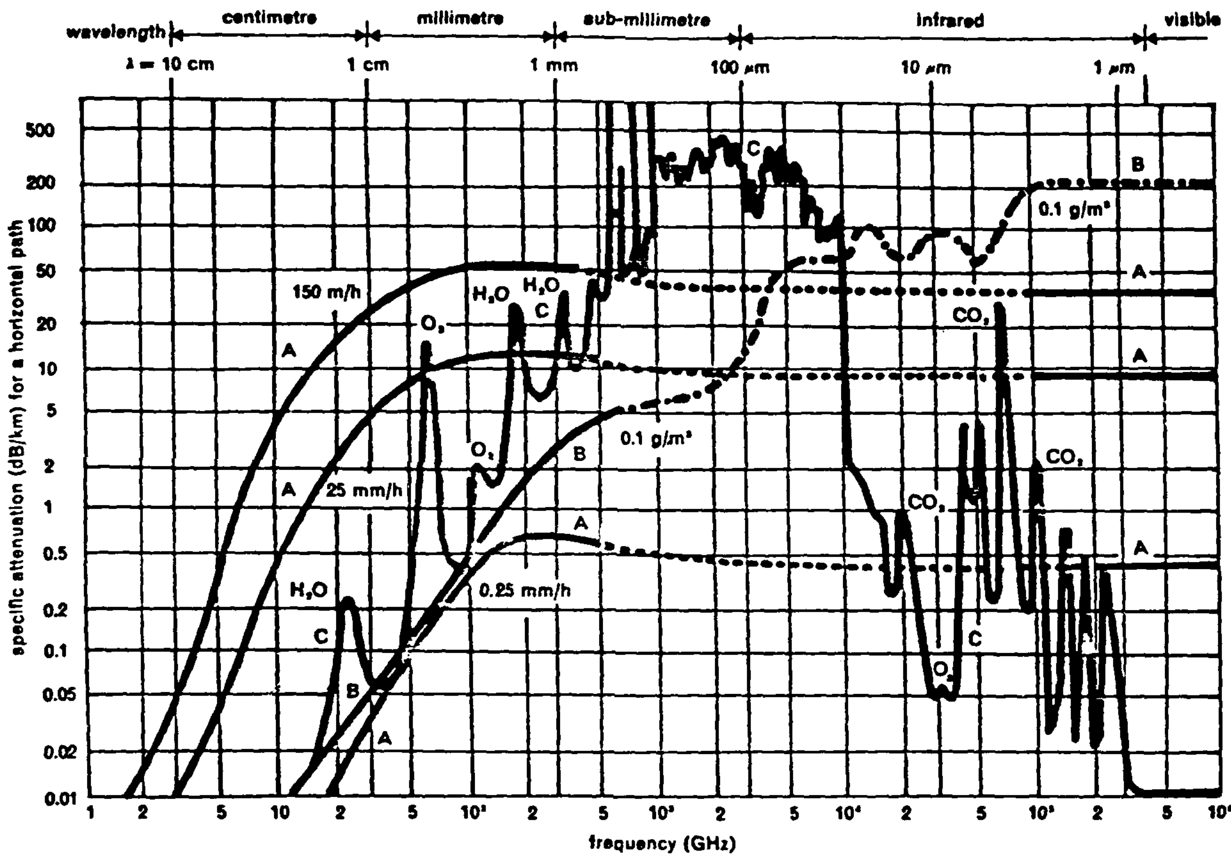

Fig. 8 — Specific attenuation of radiowaves, IR, and visible light due to atmospheric constituents. The conditions assumed: T = 20°C, vapor pressure = 7.5 gm/m^3. A = Rain, B = Fog, C = Gas. (From Bem [1979])

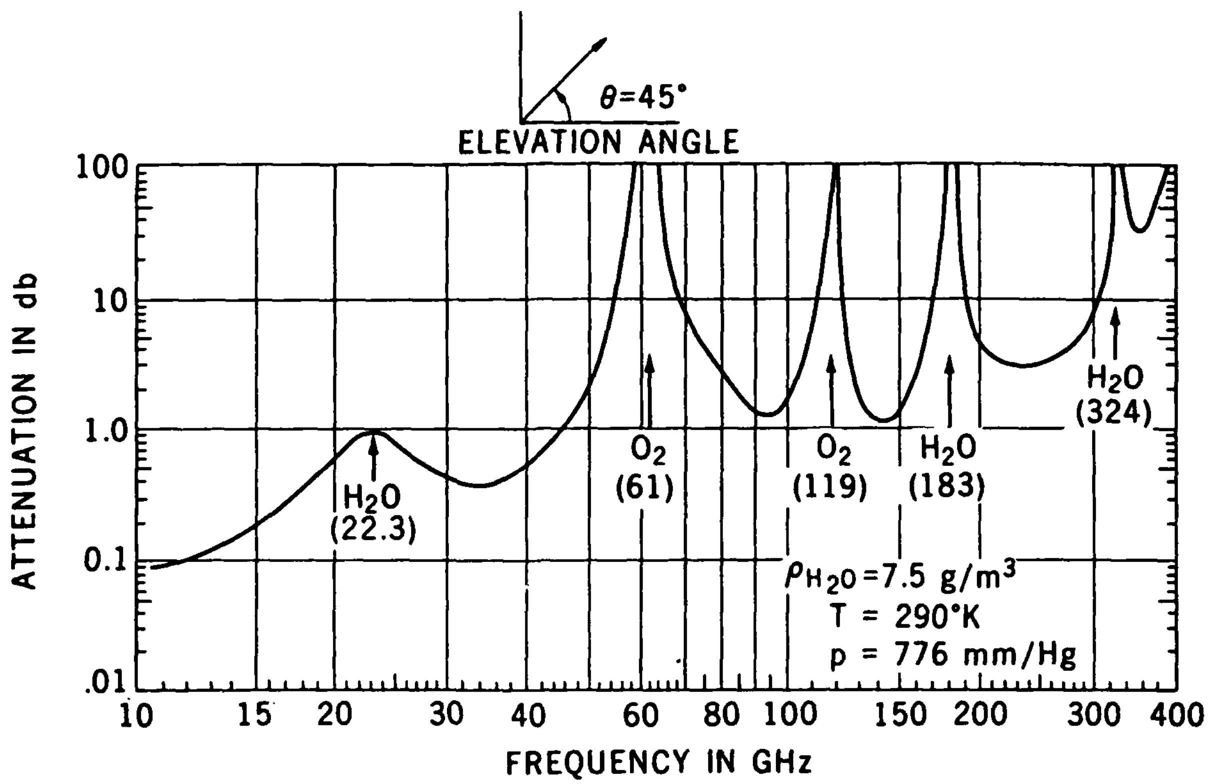

Fig. 9 — Total attenuation of the atmosphere due to resonance absorption. (From Ippolito [1978])

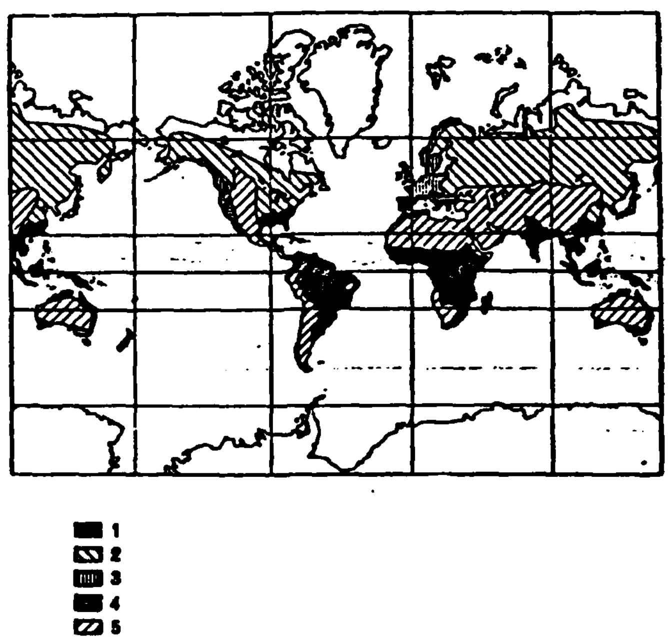

Fig. 10 — Rainfall distribution. (See Figure 11 for rain rate distributions). (From Bean and Dutton [1976])

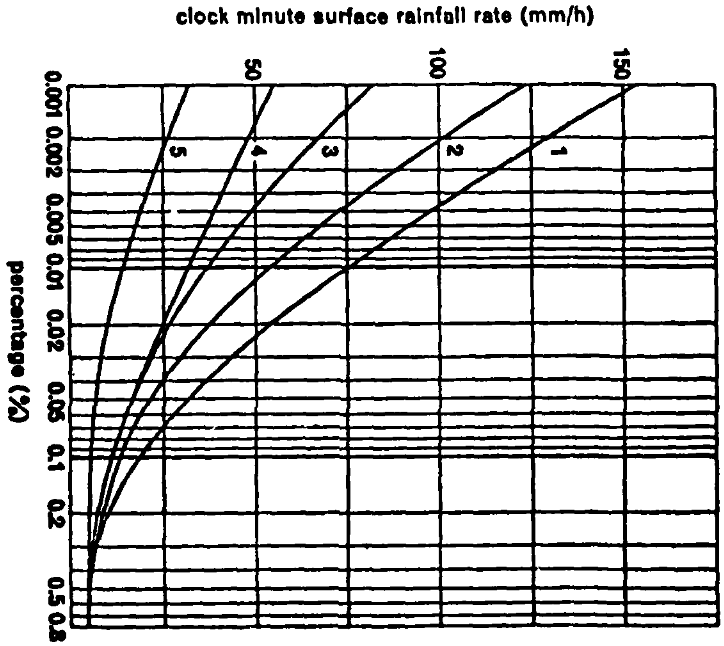

Fig. 11 — Average yearly percentage of time specified rain rate is exceeded. (Regions 1—5 are depicted in Figure 10). (From Bean and Dutton [1967])

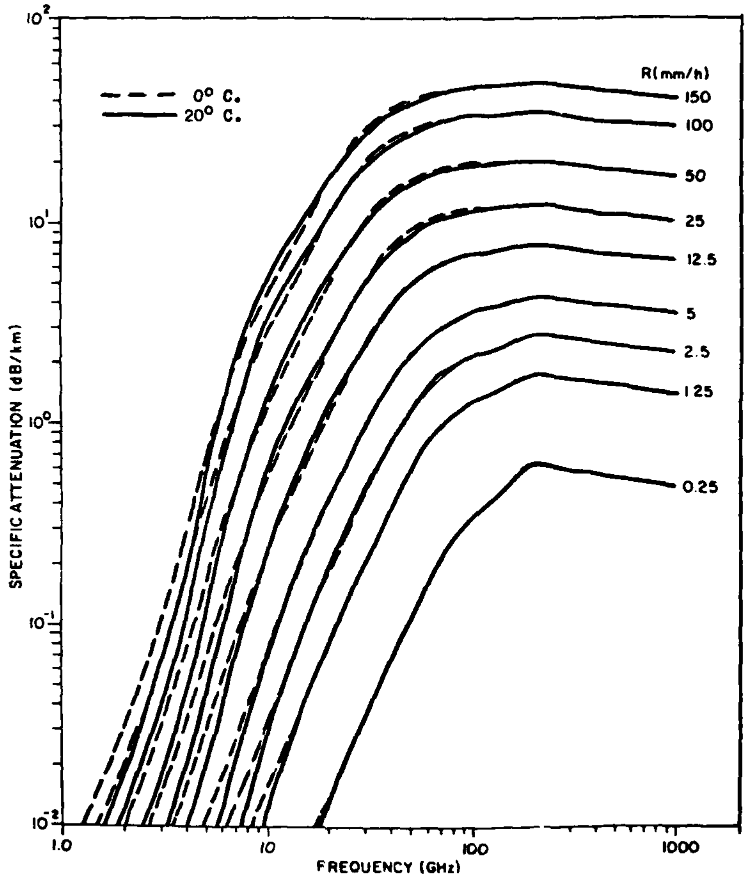

Fig. 12 — Predicted specific rainfall attenuation versus frequency (From Ippolito [1978])

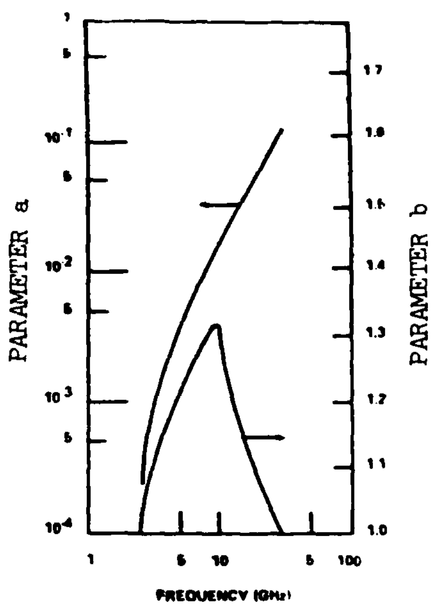

Fig. 13 — Frequency - dependent parameters a(f) and b(f). (From Beach [1979])

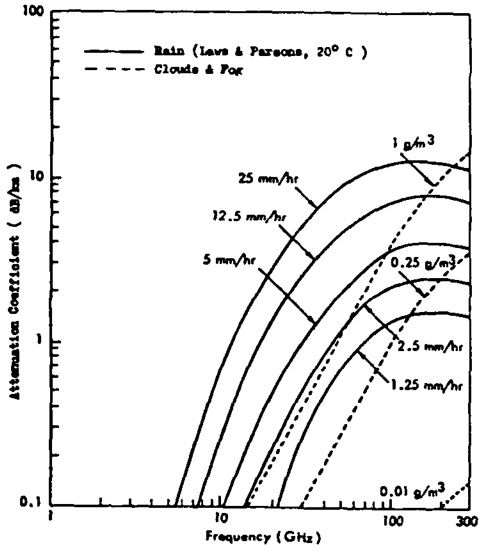

Fig. 14 — Comparison of Cloud, Fog, and Rain attenuation. (From Ippolito [1978])

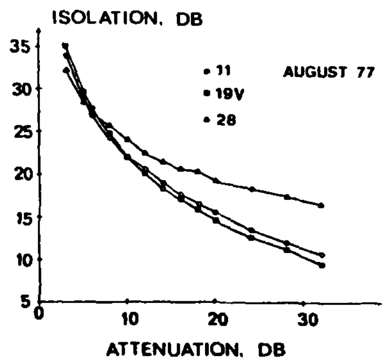

Fig. 15 — Polarization isolation (dB) versus signal attenuation (dB). (From Ippolito [1978])

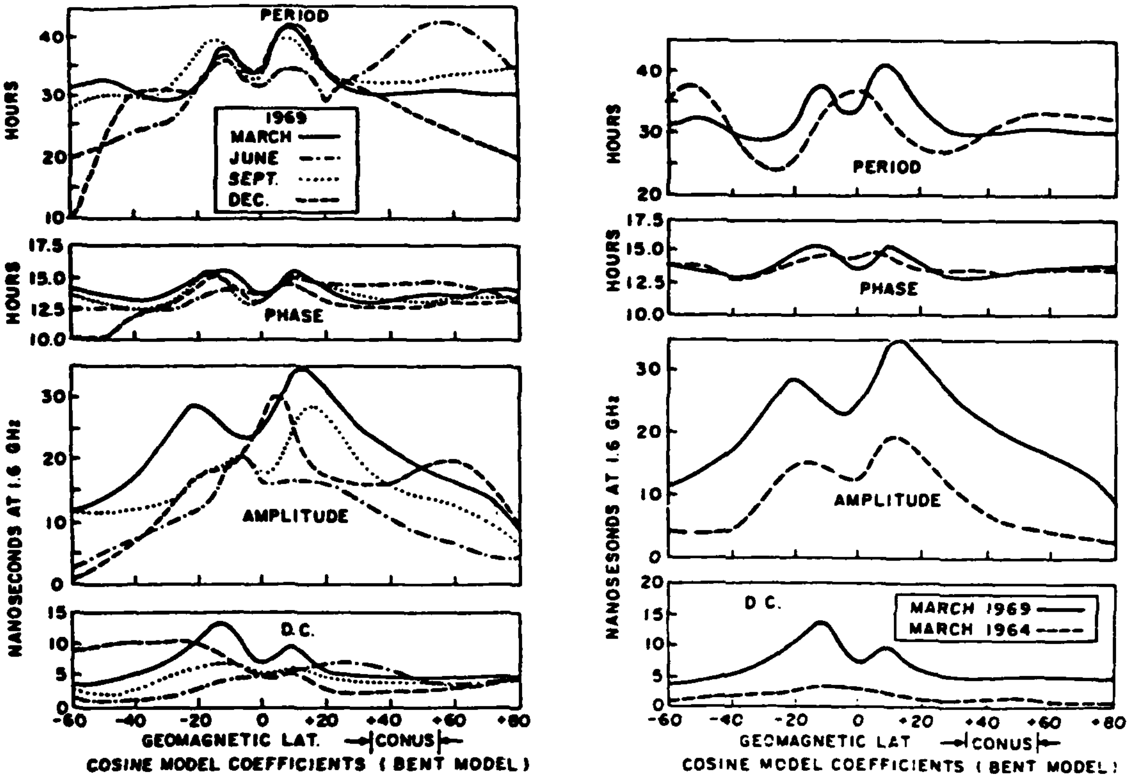

Fig. 16 — Latitudinal variation of the coefficients of ionospheric time delay. A: Seasonal effects at solar maximum; B: comparison of solar maximum and solar minimum in March. (From Klobuchar [1977])

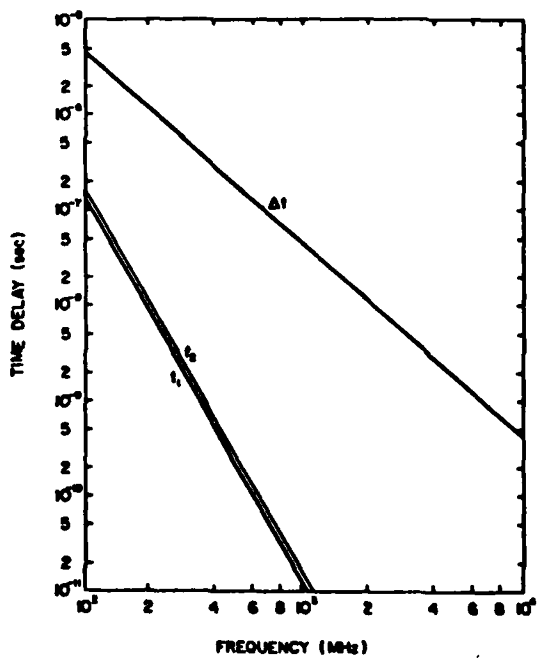

Fig. 17 — Time delay parameters ΔT (mean delay), T_1 (distortion of the pulse), and T_2 (scattering) as a function of frequency. (From Wong et al [1978])

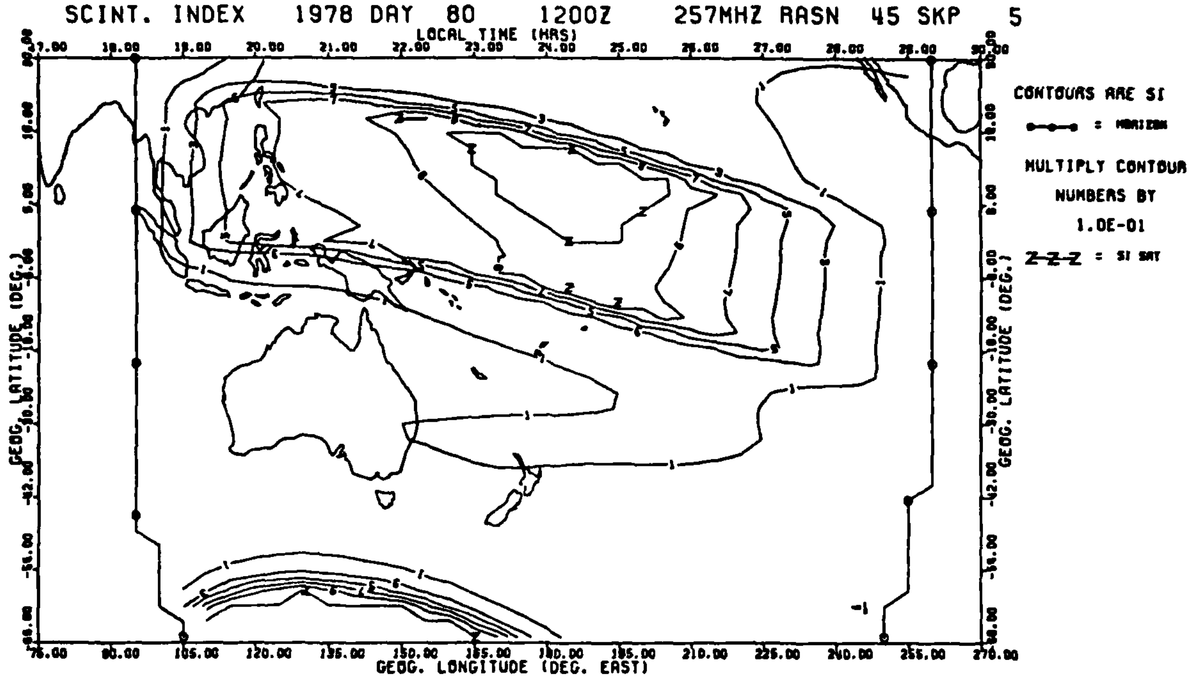

Fig. 18 — Scintillation index over the Pacific sector at a frequency of 257 MHz; other parameters are: 1200Z, Spring equinox, sunspot number 45, and $K_p = 5$. The satellite is located at 176.5°E. (From Singleton [1979])

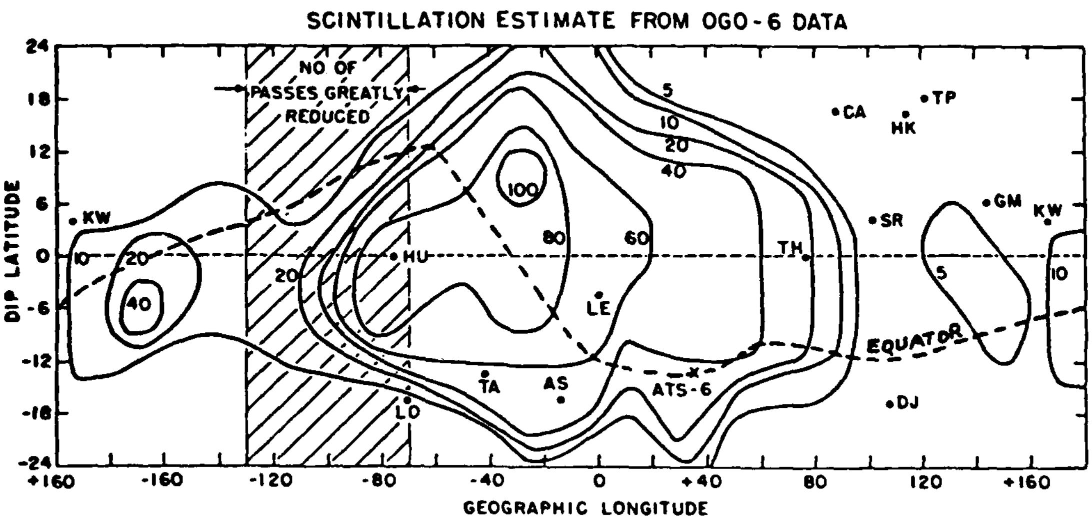

Fig. 19 — Percentage occurrence of amplitude scintillation ≥ .0.24 (given by S_4) or phase scintillation ≥ 0.1 radian at a frequency of *140 MHz. Time period Nov—Dec 1969—70 between 1900 and 2300 Mean local time.* (From Basu and Basu [1979])

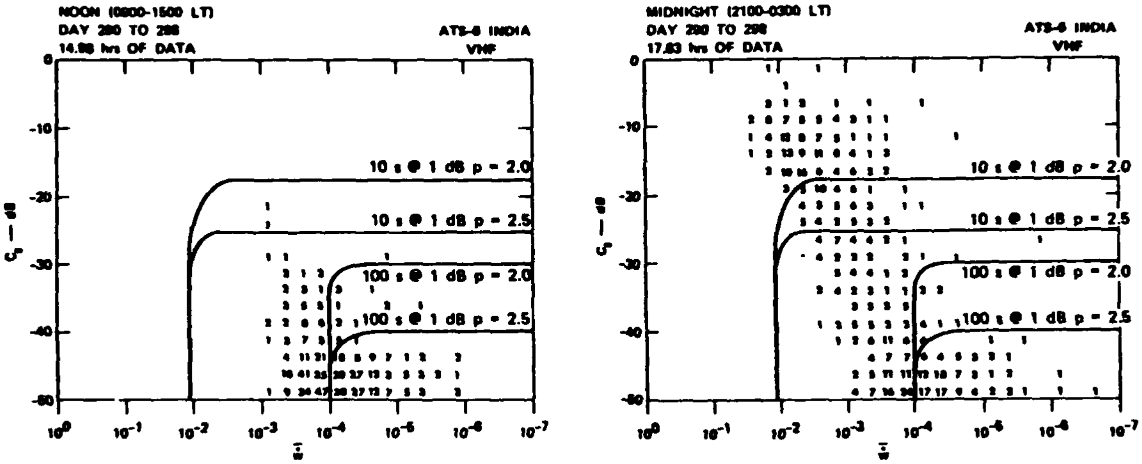

Fig. 20 — Histograms of C_S (dB) and $\dot{W}$ for both noon (A) and midnight (B) from a set of ATS-6 differential phase data at 165 MHz obtained at an Indian site. The phase spectrum is assessed to have the form $C_S f^{-p}$ where p is the power law (After Rino et al [1978])

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